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(10) Frank E. Snodgrass
and
Donald E. Stiling

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ANALYSIS OF WAVE RECORDS

by

Frank E. Snodgrass
and
Donald E. Stiling

INTRODUCTION

Due to the irregularity of ocean waves in height and period, the definition of terms employed in describing the waves is very important. The following basic definitions(8)* have been accepted:

1. Wave height is the vertical distance between the crest and the preceding trough.

2. Characteristic wave height is the average height of 33 1/3 percent of the highest waves.

3. Wave period is the time interval between the appearance at a fixed point of successive wave crests.

4. Characteristic wave period is the average period for the well-defined series of highest waves observed.

5. Wave direction is the orientation of the line of travel of the largest well-defined waves.

The definitions of characteristic wave height and period are incomplete in that the length of observation is not specified. A minimum period of ten minutes has been suggested by Scripps Institution of Oceanography(15) while a minimum of twenty minutes has been suggested by R. G. Folsom.(8) Little evidence has been published as to the effect of the length of the observation period but, as in measuring any statistical quantity, the longer the period taken the better the results, providing conditions do not change during the period. However, a long period of observation means greater expense in regard to the amount of chart paper used in recording data and the amount of time required for analyzing the the records.

ANALYSIS OF WAVE RECORDS FOR WAVE HEIGHT

In analyzing the wave records made at various locations along the Pacific Coast during the last several years, the following step-by-step procedure has been used by the University of California, Berkeley:

1. Select a continuous record of about a twenty-minute duration which was made while the recorder was operating at fast speed (three inches per minute) and at approximately the time for which wave information is desired.

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* See items in References

2. Determine the total number of waves recorded during the selected interval by:

   a. Measuring the wave period of all well-defined waves in the selected interval of the record and computing an average value.

   b. Computing the total number of waves by dividing the determined average wave period into the total seconds covered by the record interval.

3. Determine the significant wave height by:

   a. Measuring the height of the highest 33 1/3 percent of the total number of waves in the selected interval.

   b. Computing the average height of the measured values.

4. Determime the average height of the highest 10 percent of the waves as in step number three. (optional)

5. Determine the maximum wave height in the selected twenty-minute period.

Several studies have been made to determine the statistical distribution of wave height and periods about the characteristic wave heights and period. These studies do show a tendency for the wave heights to follow definite statistical distributions. Thus, the measurement of a "Characteristic" height can be used to describe the wave heights of the irregular wave trains.

Wave period distribution studies have not been as successful. The distribution of wave periods about an average, or characteristic period, is not consistent from one record sample to the next. In this sense characteristic wave periods, as determined from the above, do not describe the wave periods of the irregular waves found in nature.

One of the first of these studies, made by R. L. Wiegel[22], showed that a definite relationship existed between the average height of the highest one-third of the waves, the average height of the highest one-tenth of the waves, and the highest wave that occured in the 20 minute interval.

The ratio of the average height of the highest 10 percent to the average height of the highest 33 1/3 percent has been found to be 1.29. This ratio was determined from wave data recorded at Point Arguello, California (1.30), Point Sur, California (1.27), and Heceta Head, Oregon (1.30). A substantial number of the daily values of this ratio agreed within 10 percent with the average value derived from readings taken over a fourteen-month period at Point Sur and Heceta Head, and over a three-month period at Point Arguello.

Also from the above data, the average ratio of the maximum wave height to the average wave height of the highest 10 percent was found to be 1.46; while the average ratio of the maximum height to the average height of the highest 33 1/3 percent was found to be 1.87. Again a substantial number of the daily values of these ratios compared favorably, agreeing within 20 percent with the average value.

In a tabulation of wave data taken from two widely separated stations in the Atlantic (Cuttyhunk, Massachusetts and Bermuda) by H. R. Seiwell(19) (16), a constant of 1.57 was found for the average ratio of the average height of the highest 30 percent to the average height of all waves.

The agreement of daily values to the average values of these ratios and the agreement among values determined at widely separated stations indicated that a definite statistical grouping of waves is generated by wind.

Evidence to further substantiate this theory is found in the results of a statistical analysis conducted by R. R. Putz(13) (23) at the University of California, Berkeley. Analysis was made of twenty-five wave records selected from various localities and made at various times of the year to obtain good sampling. Putz found that the statistical frequency distribution of observed wave height in a twenty-minute interval is approximately constant in form and, for a first approximation, requires for its complete description only the determination of a typical height, such as the "significant wave-height". The wave-height distribution of all twenty-five pressure records matched, with reasonable accuracy, a Pearson Type III frequency function with a 0.8 positive skewness and proportionality of the mean and the standard deviations.

Utilizing this mathematical model, Putz computed values for ratios reported by R. L. Wiegel and H. R. Seiwell. The value of maximum wave height determined from the model was taken as the probable maximum wave in two twenty-minute intervals as used by Wiegel in determining his daily maximum wave height. Excellent agreement was found among these three sources as shown in the following table.

TABLE I

Comparison of Wave Height Ratios for Various Pressure Recorders and a Frequency Function

Basis of Calculations	Computed Ratios				Remarks
	$\frac{H_{1/3}}{H_{ave}}$	$\frac{H_{1/10}}{H_{1/3}}$	$\frac{H_{max}}{H_{1/3}}$	$\frac{H_{max}}{H_{1/10}}$	
Point Arguello, California wave recorder		1.30	1.85	1.42	3 months of data
Point Sur, California wave recorder		1.27	1.85	1.46	14 months of data
Heceta Head, Oregon wave recorder		1.30	1.91	1.47	14 months of data
Cuttyhunk, Massachusetts wave recorder	1.57				10 months of data
Bermuda wave recorder	1.57				4 months of data
Average of wave record values	1.57	1.29	1.87	1.46	
Pearson Type III frequency function MODEL	1.57	1.29	1.81	1.41	Model based upon 25 selected records

ANALYSIS OF WAVE RECORDS FOR WAVE PERIOD

Analysis of wave records for the characteristic period is accomplished by measuring the average period of the larger, well-defined waves appearing on the record. This is comparable to measuring the characteristic height of the waves by determining the average height of the highest 30 percent of the waves. The characteristic period of the waves does not describe the period-distribution, however, as the characteristic height describes wave-height-distribution. Although wave heights have been found to follow a simple mathematical distribution even though the waves may be arriving from two or more storm areas, wave periods do not follow a simple distribution if more than one generating area exists. Additional information is needed to adequately describe wave periods.

The need for more accurate methods of analyzing wave periods has led to the development of electrical-mechanical analyzers, (1) a frequency analyzer, (2) an auto-correlation function analyzer.

The frequency analyzer measures the presence of the various sinusoidal frequency components in the record to produce a frequency distribution curve. Even though this analysis may give an accurate mathematical representation of the data, the validity of its physical representation has been questioned by H. R. Seiwell[17] [18]. A study of the frequency distribution curves of pressure type wave recorders by the Oceanographic Research Group, Admiralty Research Laboratory, Teddington, England[1], and later by W. H. Munk[11] [12] indicates that this type analysis is useful in tracking storms and in correlating meteorological and wave data.

The second type of analyzer which is based on the auto-correlation function, has been investigated by the Marine Physical Laboratory, University of California[14], San Diego, California and the Woods Hole Oceanographic Institution[10], Woods Hole, Massachusetts. Although still in the process of development, this method shows promise of more accurately describing the physical characteristics of surface waves than the frequency analyzer.

ANALYSIS OF UNDER WATER PRESSURE RECORDS

The analysis of pressure records for wave period is the same as the analysis of surface wave records. The records differ, however, in that the short period waves are not registered to the same degree as the long period waves by pressure recorders due to the hydrodynamic pressure attenuation of the water. As a result, many of the shorter period waves may not appear on the pressure record.

If the technique of measuring the periods of only the larger, well-defined waves of the record is followed (as described under Analysis of Wave Records for Wave Period), the measured period will be approximately the same as would be obtained if the record were made with a surface type gage. For locations on the exposed coast, the short period waves, not recorded by pressure, are generated by local wind.

In several cases, attempts have been made to utilize the hydrodynamic attenuation of short period waves by installing gages in deep water (about 600 feet) so that only the waves of long periods (storm forerunners, seiches and tsunamis) will be recorded. These long period waves are recorded by pressure heads installed in shallow water, but are "lost" in the record of shorter period waves. Installations of this type of instrument have been made, but due to instrument difficulties no satisfactory records have been obtained.

To obtain the surface wave heights from the pressure record, two factors are required: (1) the calibration of the instrument and (2) the pressure response factor relating the subsurface pressure fluctuations to the surface wave. Thus, if

H = wave height at the surface (in feet);

C = calibration factor of the instrument (expressed in feet of water pressure variation per chart division);

K = pressure response factor based on the depth of the instrument, the depth of the water and the length (or period) of the wave being recorded;

R = reading of the instrument,

the following equation is used to obtain the surface wave height:

$$H = C/K\,(R) \quad \ldots \quad (1)$$

The calibration factor for most instruments in use today is a constant which is independent of wave period and depth of the instrument. The instrument provides a record of the pressure variations at the instrument which is accurate in amplitude and wave form.

The relation of the subsurface pressure fluctuations to the surface wave has been determined theoretically for two dimensional, irrotational motion of an incompressible fluid in the relatively deep channel of constant depth[7]. The response factor K has been shown to be:

$$K = \frac{\cosh 2\pi d/L\,(1 - z/d)}{\cosh 2\pi d/L} \quad \ldots \quad (2a)$$

where

z = depth at which the pressure variation is being measured (in feet),

d = depth of water at the instrument (in feet),

L = length of the surface wave (in feet).

When $z = d$, the pressure variation is measured at the bottom and equation 2a reduces to:

$$K = \frac{1}{\cosh 2\pi d/L} \quad \ldots \quad (2b)$$

Pressure records do not enable the direct measurement of wave length; the wave length must be calculated from the wave period using the following equation:

$$L = \left(\frac{gT^2}{2\pi}\right) \tanh 2\pi d/L \quad \ldots \quad (3)$$

Where T = wave period (in seconds).

Suitable graphs and tables[20] are available for the solution of these equations. Graphs have been prepared which enable the response factor (K) to be determined if the water depth (d), instrument depth (z), and wave period (T) are known.

Two errors arise when the above equations are used to determine the response factor (K) for ocean waves: (1) an average or characteristic period must be used in the equation while the actual wave period is continuously varying and individual waves are not sinusoidal in form; (2) wave heights computed from these equations have been shown by several observers to be from six to twenty-five percent too low.

Considering the first of these two errors, greater accuracy probably could be attained if the pressure response factor were determined for each wave and the equivalent surface wave were individually computed. This procedure might be feasible from a practical standpoint if the statistical distribution of wave height and wave period could be established so that fewer waves need be analyzed to completely describe the state of the waves. (See section: Analysis of Wave Records for Wave Height).

The second of these two errors emphasizes the need to reconsider the basic theory which does not agree with experiment. Every observer who has simultaneously measured the surface waves and the subsurface pressure fluctuations has found the theoretical response factor determined from equation (2a) to be too small. Ten random measurements made at the Waterways Experiment Station[24] indicated an average correction of 1.07 should be applied to the response factor. Seventeen laboratory measurements at Berkeley indicated an average correction of 1.10[8]. Field data reported by the Woods Hole Oceanographic Institute[1] [16] indicated a correction factor in excess of 1.20 while the three sets of field data obtained by the University of California[6] indicated values of 1.06, 1.08, and 1.18.

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APPENDIX

STATISTICAL ANALYSIS OF OCEAN WAVES

The wave recorder is programmed to run at slow-speed (3 inches per hour) for 5 hours and 35 minutes, and at fast-speed (3 inches per minute) for 25 minutes. When definite and pronounced increases in wave amplitudes (indicating the arrival of wave trains) are evident on the slow-speed portion of the record, the time and date of these arrivals are noted by the analyzer. Only the fast-speed sections of the chart are analyzed for wave height and period. A twenty minute interval is selected for determining characteristic wave period and maximum and characteristic wave heights. Except in cases of storm arrivals, as previously mentioned, the records are analyzed at twelve-hour intervals. Records are analyzed every six hours during storm periods or when the slow speed portion of the record indicates rapidly changing conditions.

To standardize practices used in the analysis of ocean waves from underwater pressure-head records, the following list of definitions has been accepted.*

1. Wave height is the vertical distance between the crest of a wave and the preceding trough.

2. Characteristic wave height is the average height of 33 and 1/3 percent of the highest waves.

3. Wave period is the time interval between the appearance at a fixed point of successive wave crests.

4. Characteristic wave period is the average period for the well-defined series of highest waves recorded.

5. Wave direction is the orientation of the line of travel of the largest well-defined waves.

PROCEDURES FOR ANALYZING WAVE RECORDS

The following steps in the procedure for analyzing wave records have been developed over a period of several years at the University of California.

Receipt of the Record:

The graphic chart represents the time history of the surface wave action and should be the final authority in case of future conjecture as to the validity of statistical information compiled therefrom. Hence, a system of logging charts is used for facility of future reference. The log of records contains (a) the time and date the run began and ended, (b) the number of the chart (i.e., its chronological sequence) and (c) the date the record was received. Following is a form which has been used for logging records.

LOCATION ________		START		END		REMARKS
Received	Roll No.	Time	Date	Time	Date	

Log for Mark IX Wave Recorder Charts

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* Folsom, R. G.; "Measurement of Ocean Waves"; TRANSACTIONS of the AMERICAN GEOPHYSICAL UNION, Vol. 30, No. 5; October 1949.

Reading the Chart:

A. Frequency of taking Samples

1. The wave records are analyzed during the fast-speed portion of the chart at approximately twelve-hour intervals. Recorders are programmed to obtain fast-speed records at 6 A.M., noon, 6 P.M., and midnight.*

2. Manual operation of the chart speed is provided on all records. Additional samples may be obtained by the operator during storm periods. The frequency of these samples and the number of the records analyzed is left to the discretion of the operator and analyst.

B. Establishing the point in time of readings

1. The beginning time should always be marked on the chart when a new roll is placed in operation, and also when it is removed from the recorder.

2. If possible, time checks should be made on the chart during the recording period together with supplementary remarks concerning the character of the surface waves.**

3. A progressive time determination is made assuming six hour intervals between the beginningsof the fast-speed runs. The time at any point on the chart can be determined by measuring the chart length (or counting divisions) from the known time.***

4. The time of the reading is defined as the mean time of the interval chosen for analysis. (See C "Selection of Interval.)

C. Selection of Interval to be Analyzed Within the Fast-Speed Portion of the Chart

The programming of the fast-speed portion of the wave record would logically be a direct function of the average period of waves during that portion. That is, the analysis is normally based on a given number of waves, and for equal numbers of waves measured per interval, one would select short and long fast-speed intervals for waves of shorter and longer periods, respectively. While this would be statistically consistent, it would require the impracticability of period forecasting and the inconvenience of variable programming, or the use of an excessive amount of chart paper. Hence the following plan is used, based on the analysis of a fixed time interval.

1. Select the interval to include 20 minutes of the fast-speed portion and, if possible, select this interval such that its mid-point will approximately coincide with the mid-point of the fast-speed run. This assumes a fast-speed run to be approximately 25 minutes in length.

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* The Sangamo Timer used for programming the frequency of fast runs and their duration may be used in a number of combinations.

** These periodic remarks should include time of observation, direction of waves as defined on page 1 of this report, the stage of the tide, and descriptive remarks about the character of the water surface--such as calm, rough, white caps, etc.

*** Fast chart speed corresponds to 3 inches per minute, slow chart speed corresponds to 3 inches per hour.

2. In the event that this interval cannot be taken (due to the end of the chart or variation in cam action of the programmer), select as great an interval as may be possible, centering the interval so that at least one minute is allowed at the beginning of the interval in order for the chart speed to reach its full speed (particularly if the spring wound recorded is used).

A typical wave record has been analyzed and reproduced here to illustrate the analysis procedure. Notice that the time of the beginning of the sampling interval is 0829 whereas the beginning time of the fast-speed run is at 0827. An interval of 20 minutes has been selected in this fast-speed portion, hence the end of the sampling interval is 0847.

The time of the interval being centered within this 20 minute interval is, therefore, 0839.

D. Determination of the Characteristic Period

1. Having defined the sampling interval, the next step is to select several groups of waves, within the interval, that contain a series of well-defined waves.

2. Measure the length of time from the beginning to the end of each of the series of well-defined waves and count the number of waves included in this series.

3. Divide the sum of the time-intervals of the groups of waves by the total number of waves counted in all such groups.

Thus $T_c = \frac{t}{n}$

where: t = total time interval between the beginning and end of all well-defined series of waves.

n = total number of waves included in all of the series.

T_c = The Chracteristic Wave Period.

From the example, we see that there have been six such groups of waves selected and that the characteristic period of this interval is found to be:

$$T_c = \frac{n}{t} = \frac{44+87+193+75+103+114}{3+6+13+5+7+8} = \frac{616}{42} = \underline{\underline{14.7 \text{ sec}}}$$

E. Determination of the Number of Significant Waves to be Measured

1. Divide the interval by the characteristic wave period to determine the number of waves within the interval.

For example:

$$\frac{\text{Interval (in seconds)}}{\text{Period (seconds per wave)}} = N \text{ number of waves}$$

$$\frac{20 \times 60}{14.7} = \frac{1200}{14.7} = 82 \text{ waves}$$

2. Measure the highest N/3 waves $\left(\frac{N}{3} = \frac{82}{3} \approx 27\right)$*

   (a) Scan the record selecting the highest waves observed until N/3 waves are selected.

   (b) Measure the height of the waves in divisions and record.

As may be seen on the sample analysis Data Sheet, the values of the wave heights have been recorded, the remaining part of the analysis being to arrive at the significant wave heights from these data.

F. Determination of Significant Wave Heights

1. Determine the average of the highest N/3 waves as recorded (in this case 27 waves). Since the waves are measured in terms of the recorder chart divisions, the designation of this average is $R_{1/3}$. From the example, $R_{1/3} = 15.9$**.

2. Record the maximum wave height encountered R_{max}, in this case 19.5 divisions.

G. Evaluation of Wave Heights from Chart-divisions to Wave Height in feet-of-water

1. The following equation is used to obtain the surface wave height:

$$H = \frac{C}{K} R \tag{1}$$

where: H = wave height at surface, in feet.

C = calibration factor of the instrument in $\frac{\text{Feet of Water Pressure}}{\text{Chart Divisions}} =$

K = pressure response factor based upon depth of the instrument, depth of the water and length (or period) of wave being recorded.

R = reading (in divisions) taken from chart as shown above.

2. Since the characteristic wave height and the maximum wave experience are the only two surface wave heights required in compiling the statistical information, only the values from the preceding determination need be used as the value of "R" in the above equation (1).

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* In the example given, the highest 30 waves have been selected for measurement, and after measurement, the three lowest of this group have been omitted from the average. Normally, the analyst need select only 1/3 of the waves for measurement.

** Omitting 12, 12.5, 12.5 (three lowest values of the 30 selected for measurement).

Example:

$$H_{1/3} = \frac{R_{1/3}}{K} C$$

$$H_{1/3} = \frac{15.9}{0.822} 0.0755 = \underline{1.46 \text{ feet}}$$

$$H_{max} = \frac{19.5}{0.822} 0.0755 = \underline{1.79 \text{ feet}}$$

3. The value of C, 0.0755, was determined by laboratory test.

4. The values of K for various conditions of depth, period, etc. may be readily computed or obtained from prepared tables and graphs*.

H. Recording the Statistical Information

The purpose of analyzing wave data is to finally compile statistics that give a time history of the characteristics of surface waves. This information may be tabulated on a form as shown below and eventually may be graphed to a time scale.

CHARACTER OF THE SEA TABLE

AT ______________________ FROM ____________ TO ____________

DAY	HOUR	T	$H_{1/3}$	H_{max}	REMARKS

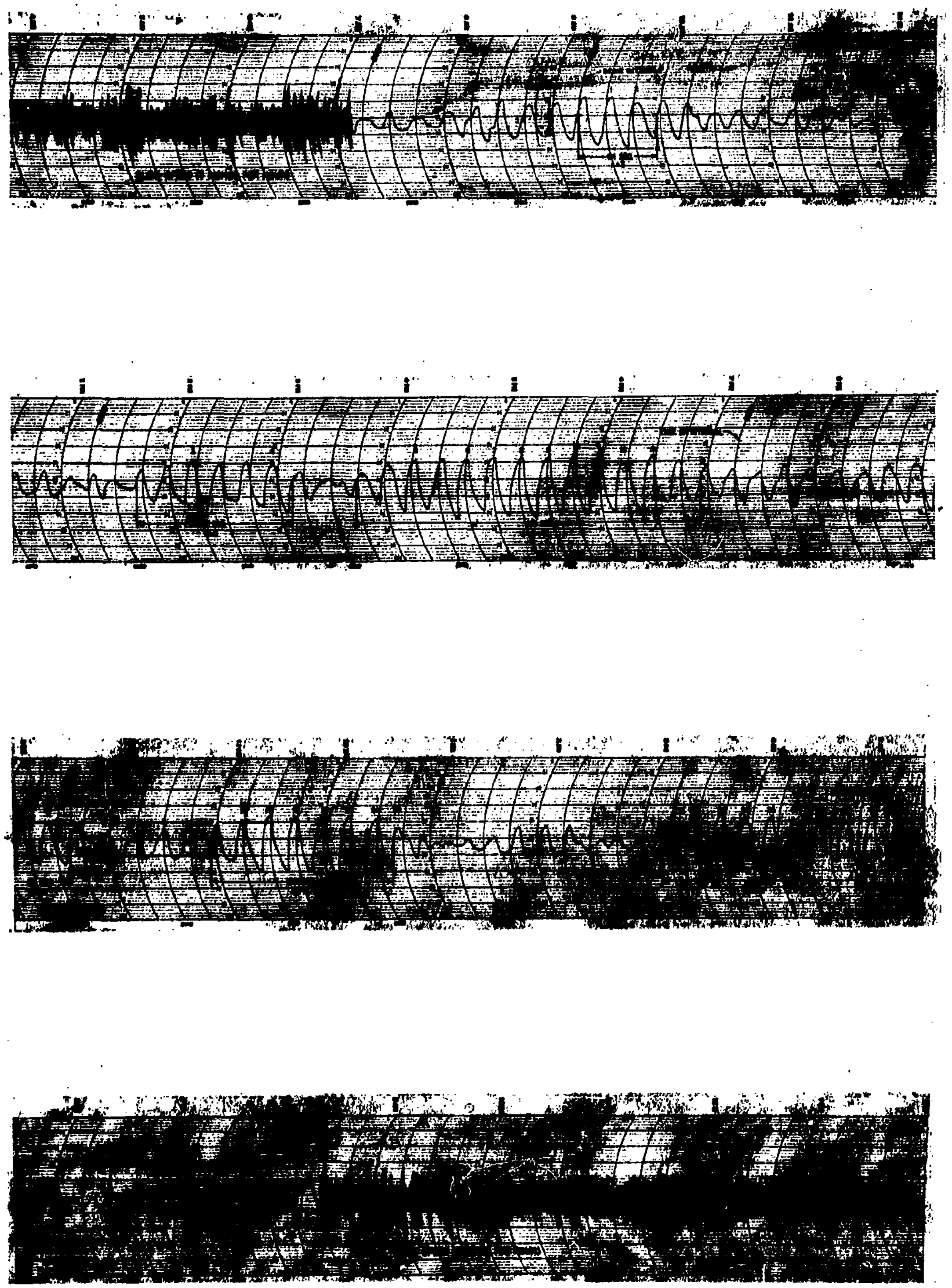
* Wiegel, R. L., PRESSURE RESPONSE AT THE OCEAN BOTTOM DUE TO SURFACE GRAVITY WAVES, Technical Report HE-116-108, University of California, Department of Engineering, Fluid Mechanics Laboratory; Berkeley, California; September 1948.

SAMPLE ANALYSIS--DATA SHEET
POINT SUR, CALIFORNIA

ROLL NUMBER DATE TIME OF READING PERIOD N/3	273 May 11, 1950 0839 13.6 sec. 27			
WAVE NO.	WAVE HEIGHT - IN DIVISIONS			
1	14			
2	13.5			
3	13			
4	12.5*			
5	15			
6	17.5			
7	16			
8	17			
9	18			
10	19.5			
11	18			
12	14.5			
13	18			
14	15.5			
15	12.5*			
16	12 *			
17	17			
18	16.5			
19	18			
20	18.5			
21	13			
22	13			
23	17			
24	17			
25	16			
26	18.5			
27	14			
28	12.5			
29	15			
30	15			
R_{max}	19.5			
$R_{1/3}$	15.9			
K	0.822			
$H_{1/3}$	1.46 Ft.			
H_{max}	1.79 Ft.			

K, the ratio of the subsurface pressure to the surface wave height, was determined for a depth of water of 65 feet and for an average period of 14.7 seconds.

* These values were not used (see footnote **, page 11).



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